Fast-Ignition Inertial Confinement Fusion Research*

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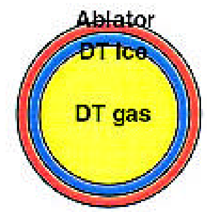
Outline

- What ICF is and what makes it difficult
- Fast Ignition: a more efficient path to ICF ignition and gain?
- 3 major research issues in Fast Ignition ICF
    - Selected theoretical and experimental results from world-wide research
- Summary: Where are we now and where do we need to go?

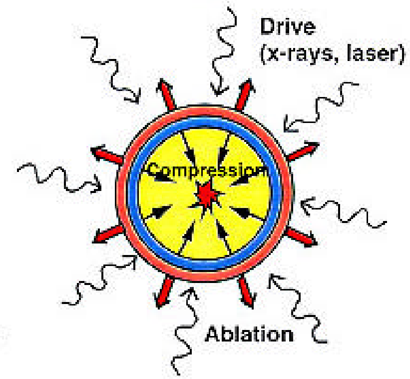
Conventional ICF implosions create their own ignition hot-spot

- Symmetric drive heats and ablates an outer shell surrounding frozen DT fuel; rocket effect compresses remaining shell+fuel

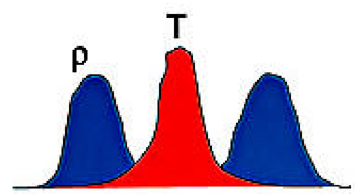


- Drive vs. time tailored to maintain low fuel entropy for high compressibility

- Final stagnating state persists long enough to equilibrate pressures (isobaric)
    - Central low-ρ hot spot serves as spark
    - Colder high-ρ main fuel surrounds hot spot



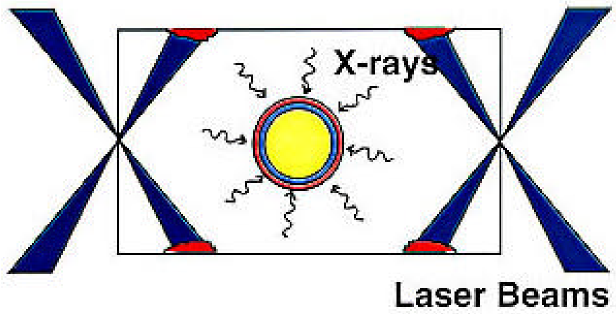
- Ignition occurs when α-particle heating overcomes conductive heat losses from hot spot
    - Hot spot: T ~ 10 keV, ρR ~ 0.3 g/cm^2
    - Main fuel: ρR ~ 3 g/cm^2 for 33% burn efficiency



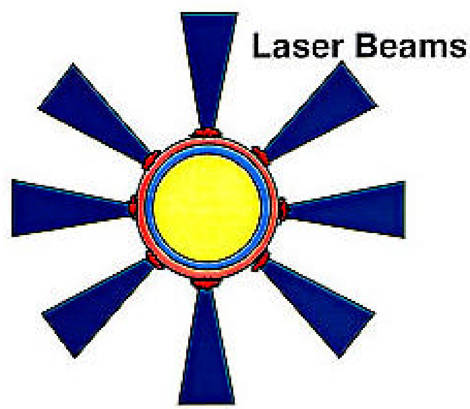
- Gain scales as ~ $E^{2/3}$ at high E (~ 10X at E_{laser} = 1 MJ)

ICF drive is direct or indirect

- Indirect drive
  - Laser or particle beams generate confined ~ 300 eV blackbody which irradiates the capsule with x-rays
  - Very symmetric drive; deep x-ray penetration into shell reduces hydro instabilities



- Direct drive
  - Laser beams directly irradiate capsule
  - Symmetry is difficult to achieve (laser, capsule); efficient, laser-plasma interaction problems are simpler

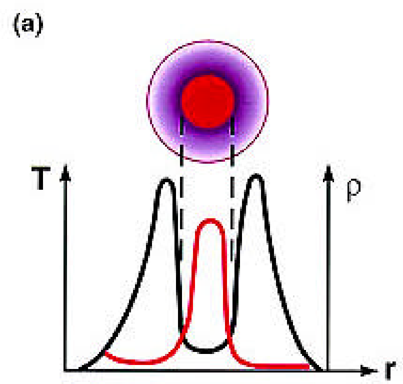


Conventional isobaric hot-spot ignition places stringent demands on implosion parameters

- Hot-spot ignition is necessary with attainable ICF drivers
  - Requires high compression $\Rightarrow$ High input energy
  - Hydro instabilities and radiative losses require solid (cryogenic) DT pusher
- Ignition threshold energy determined by achievable implosion velocity V_{imp}
  - Laser-plasma interactions are upper limit to V_{imp}
  - Hydro instabilities are lower limit to V_{imp}
- Exquisite symmetry and pulse-shaping, high convergence (high fuel ρ) are required to attain necessary hot spot ρR and T, main fuel ρR

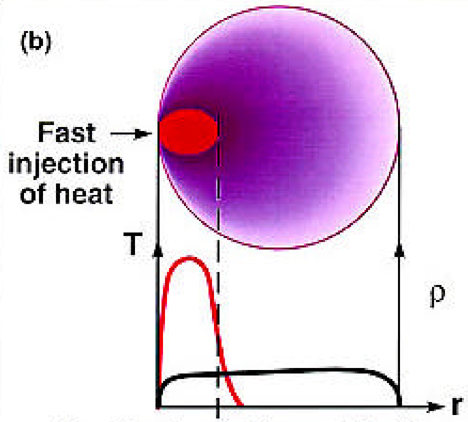
The difference between FI and conventional ICF is simple at the conceptual level

Conventional ICF	Fast Ignitor



Low-density central spot ignites a high-density cold shell

$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)



Fast-heated side spot ignites high-density fuel ball

$\rho_{hot} \approx \rho_{cold}$ (isochoric)

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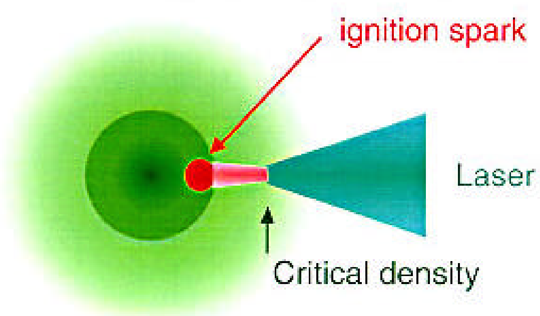
FI is an alternative approach to achieving ICF ignition and gain

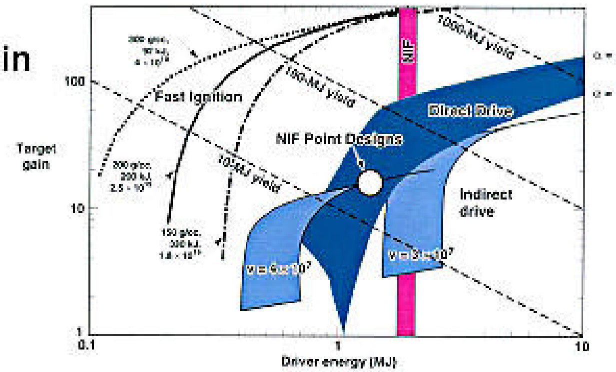
- *Isochoric* fuel is heated by an *external* source
    - Fuel may have a uniform compressed (relatively low) ρ
    - No central isobaric hot spot
- *High-ρ* spark is generated by an external ultraintense laser
    - Laser self-channels through low-ρ plasma
    - Energy is converted to relativistic e's up to critical density
    - Electrons transport energy to high-ρ fuel and heat it to ignition
- Hot spot ~ 0.5 g/cm^2, 10 keV; main fuel still ~ 3 g/cm^2
- *Final fuel configuration is very different and requires less energy to assemble*



M. Tabak, Phys. Plasmas 1, 1626 (1994)

FI may be more efficient than conventional ICF and is more promising for IFE

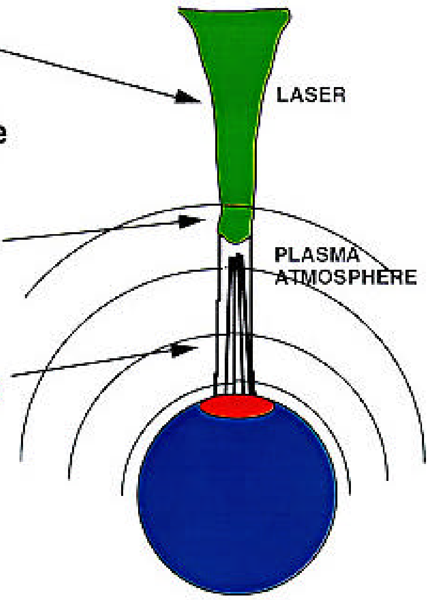
- Isochoric compression is cheap
    - No need to form central hot spot in pressure equilbrium
    - High fuel ρ not necessary
    - Low energy in ⇒ high gain



- Symmetry and pulse-shaping requirements are less stringent
    - Lower fuel ρ is o.k. ⇒ symmetry requirements reduced
    - Mixing and preheat acceptable ⇒ more E/P phase space can be used
- Target fabrication is simplified
    - Super-smooth surfaces (especially on DT ice) are not necessary
    - Liquid DT or DT-doped solid fuels may be possible

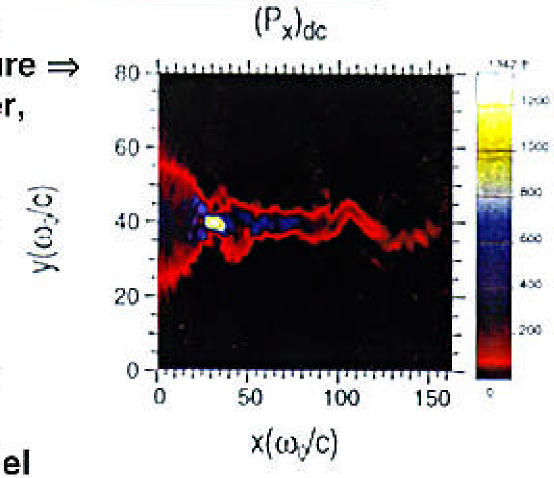
3 main areas of Fast Ignitor physics are being researched world-wide

- Ultra-high-intensity (UHI) laser propagation in plasmas
    - UHI laser must penetrate low-ρ plasma $\Rightarrow$ future hot-spot subtends larger Ω
- Absorption of UHI laser into relativistic e's up to N_c
    - Conversion efficiency, spectrum
- Transport of and heating by relativistic e's in high-ρ plasma
    - Instabilities; beam spraying and magnetic collimation
    - Absorption in main fuel
- Two other areas will not be discussed in detail here
    - Implosion optimization
    - Construction of suitable UHI laser



#1: UHI Laser propagation in plasmas

- High-intensity lasers tend to self-focus in a plasma due to radial ponderomotive pressure ⇒ Radial expansion, local ρ minimum at center, and self-guiding



- Relativistically high-intensity (> 10^{18} W/cm^2) lasers have additional filimentation and self-focusing mechanisms
    - Ponderomotively created electrons are Lorentz-force accelerated *forward* (Relativistic B field), filimented by Weibel instability
    - Radially-dependent relativistic corrections to plasma frequency and index of refraction create self-focusing
    - Light follows electrons and can filiment with them
- Channelling is important for FI: Moves electron source closer to fuel

#1: Selected UHI laser transport research results

- Young @ LLNL (PRL 75, 1082 (1995)): Demonstrated well-modelled self-channeling in underdense plasma with a 10^{16} W/cm^2, 300 - 500 ps laser pulse

- Pukhov @ Max Planck Institute (PRL 76, 3975 (1996)): 3D PIC simulations show relativistic self-channeling greater than 40 wavelengths deep at 10^{19} W/cm^2 with sub-ps pulses

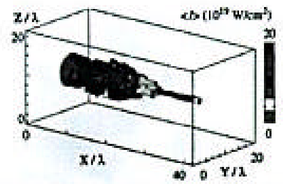


FIG. 1 (color). Perspective view of the self-focusing pulse at time 180 fs. The colors refer to the maximum cycle-averaged light intensity (I_{max}) in each (Y,Z) plane; the plotted surface corresponds to $0.67I_{max}$.

- Borghesi @ Imperial College (PRL 78, 879 (1997)): Demonstrated relativistic self-channeling with a 1 ps, 10^{19} W/cm^2 laser, forming an unstable channel in underdense plasma ~ 100 μm long

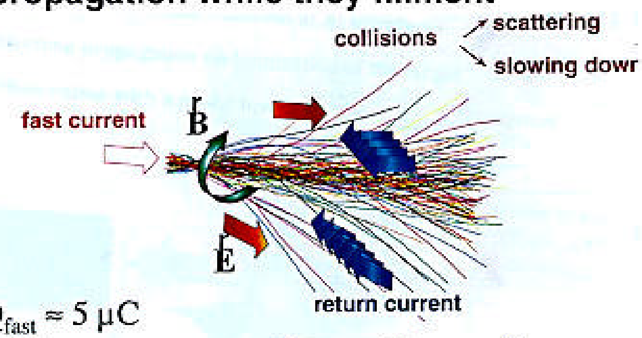
FIG. 3. Self-emission (λ = 0.527 μm) channel of Fig. 2 showing oscillations in transverse size

- Fuchs @ INRS Quebec (PRL 80, 2326 (1998)): Demonstrated > 10% light transmission through $10n_c$ plasma at 10^{19} W/cm^2 due to relativistic transparency

#2: Absorption of UHI laser into relativistic electrons

- Electrons are liberated by many processes, including field ionization in underdense plasma
- Electrons are accelerated longitudinally by Lorentz force, escape up density gradient into dense plasma with $E \sim U_{pond}$
  - $U_{pond} \sim 0.511$ MeV $(I_{18})^{0.5}$ for I >> 10^{18} W/cm^2
  - Energy conversion efficiency can be ~ 50%
- Magnetic fields are in the multi-mega Gauss range; surround electrons and confine their propagation while they filiment

Efficient conversion to electrons with the proper energies is important for FI

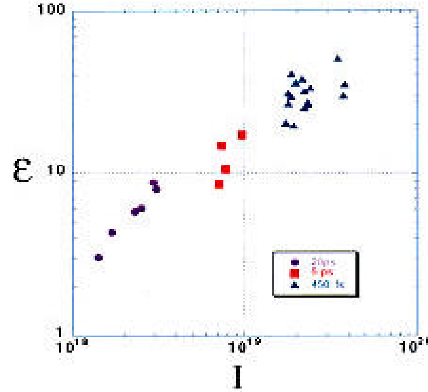


$Q_{fast} \approx 5\ \mu C$
$\tau < 1 ps$
$I_{fast} \approx 10^{12}\ A/cm^2$
$\varnothing \approx 20\ \mu m$

→ What will occur ?

#2: Selected relativistic electron conversion research results

- Malka @ CEA (PRL 77, 75 (1996)): Show $T_{hot} \sim U_{pond}$ for a 0.5 ps 10^{19} W/cm^2 laser incident upon a solid



- Wharton @ LLNL (PRL 81, 822 (1998)): Demonstrated 20-30% conversion efficiency into relativistic electrons with T_{hot} > 600 keV at 10^{19} W/cm^2 in solid Cu

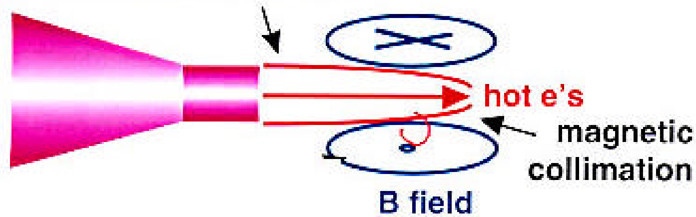
- Pukhov @ Max Planck Institute (Fast Ignition Workshop, 1998): 3D PIC simulations show $T_{hot} \sim 3U_{pond}$

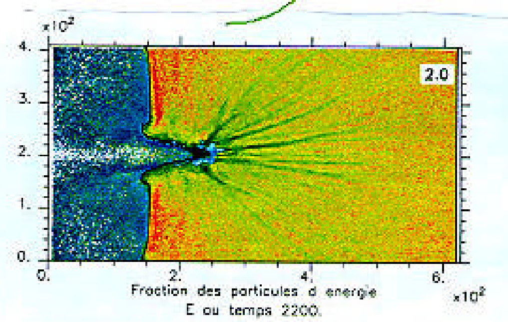
- Cowan @ LLNL (PRL 84, 903 (2000): Demonstration of super-hot electron production up to 100 MeV via photonuclear fission measurements

#3: FI requires that the electrons propagate through dense plasma and ignite the fuel

- Electrons are collimated by self-generated magnetic fields and central resistivity decrease due to heating
- Electrons stop in fuel and heat it
  - Range depends on conductivity and T_{hot}
- Electron transport and energy deposition are key steps in FI process

Weibel instability causes filamentation of current





PIC calculation (JC Adam, S Heron France) shows Weibel filamentation at 10^{20} Wcm^{-2}

#3: Selected relativistic electron transport and heating research results (1)

- Hall @ U. of Essex (PRL 81, 1003 (1998)): Observed electron deposition in shock-compressed solid plastic targets, larger deposition lengths than cold targets due to enhanced conductivity

- Koch @ LLNL (Lasers and Part. Beams 16, 225 (1998)): Measured thermal heating by hot electrons at 5-20 μm depths with 10^{17} - 10^{19} W/cm^2 laser pulses, with several hundred eV tempertures at near solid density

- Borghesi @ Imperial College (PRL 81, 112 (1998)): Multi-mega gauss B fields inferred from Faraday rotation measurements with solid targets

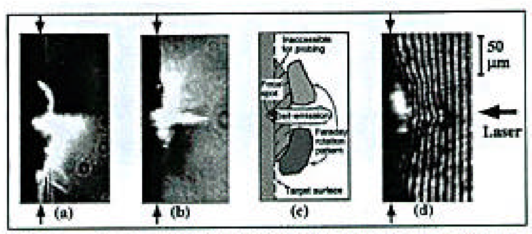
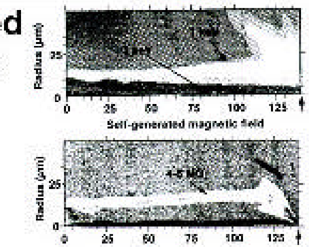


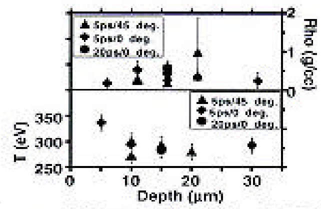
FIG. 1. (a), (b) Polarigrams taken 12 ps after the interaction of a 10 TW, 1.5 ps laser pulse with a solid Al target, with the two polarizers −9° and +12° off crossed. The position of the target surface is indicated by the arrows. (c) Schematic showing the main features of the polarigrams. (d) Interferogram recorded 15 ps after the interaction.

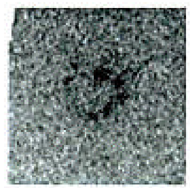
#3: Selected relativistic electron transport and heating research results (2)

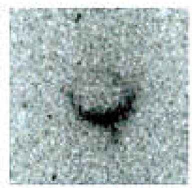
- Davies @ Imperial College (PRE 59, 6032 (1999)): Simulated e-transport in solids; predicted jets of e's due to magnetic collimation and low-resistivity channelling



- Koch @ LLNL (IFSA '99 workshop): Measured > 200 eV temperatures in tracers buried < 200 μm into solid CH; collimated transport and ring emission







- Gremillet @ CEA (PRL 83, 5015 (1999)): Observed electron jets in transparent solids by shadowgraphy at 10^{19} W/cm^2; jets apparently broken into filiments several hundred μm long

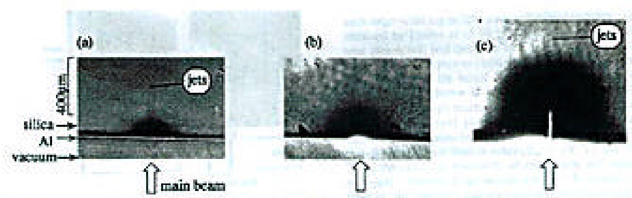


FIG. 2. Shadowgraphic images of the silica target at three times, (a) 1.2 ps, (b) 2.2 ps, and (c) 3 ps after the interaction pulse. Note that in (a) the fringes inside the cloud are an artifact of the image subtraction process (the diffraction pattern at the target edge being present only in the reference image).

Issues we understand

- Basic advantages of FI concept for ICF ignition and gain are understood
    - Hot-spot parameters required
    - Final fuel configuration which must be penetrated and heated
- Ponderomotive and relativistic self-guiding of lasers in plasma is understood in principle and has been observed in experiments
    - Numerous subtleties
- Energy conversion to relativistic electrons is understood in principle and has been quantified
    - Again, numerous subtleties

Outstanding issues in FI research

- Electron conversion efficiency: what parameters determine it?
- Electron transport and heating
  - Simulations and data exist for solid targets; little for dense plasmas
  - Conductivity, role of return currents is complex
  - Heating by relativistic electrons is less than expected in the few experiments which have looked
  - General correspondance between solid-target experiments and dense fully-ionized plasmas is not clear; the latter is difficult to realize in experiments, the former is very complex
- Integrated laser pulse shaping for FI
  - Long leading channelling pre-pulse + short UHI pulse

In the coming years we can expect progress in several critical areas

- Experiments and theory firming our understanding of conversion efficiency and the parameters which determine it
- Electron transport experiments and theory
  - Collimated transport and heating in solid targets
  - Pre-form plasma experiments
- Laser engineering
  - Petawatt upgrades at LULI and RAL
  - Higher intensities or longer pulses by more energy
- Numerous sideshows
  - A major byproduct of FI research is a general understanding of the physics of UHI laser/matter interactions

Conclusions

- Fast-ignition is a promising approach to ICF ignition and gain
    - Reduced energy requirements for assembling fuel
    - Reduced symmetry requirements
    - Greater potential for IFE
- World-wide research has produced substantial progress in understanding the critical issues involving UHI laser heating of the imploded fuel
- Continued research on increasingly large UHI laser facilities will address issues which remain poorly understood